# Comparison of moisture buffering properties of plasters in full scale simulations and laboratory testing

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**Abstract**

The regulation of indoor relative humidity is a key factor for the provision of occupant health and comfort. Passive humidity regulation is possible if porous materials, for example clay and gypsum plasters, are exposed to the indoor environment. Materials that are highly hygroscopic can help regulate relative humidity levels through their capacity to adsorb and release water vapour from and to the indoor air via a dynamic process referred to as moisture buffering. Laboratory test methods have been developed to measure this moisture buffering capacity, which are well-suited for comparative testing of relatively small material samples under controlled conditions. However, quantification of the impact of hygroscopic materials in real buildings requires additional evaluation, like field testing and the support of simulation models, which can successively be used for the development of new protocols capable of giving information about materials' moisture buffering performances indoors.

This paper investigates moisture buffering capacity of three hygroscopic plasters (clay, gypsum and lime), and compares measurements obtained in the laboratory to those from numerical simulations of a single-zone room space. The dynamic sorption capacity of the plasters was investigated using the NORDTEST protocol and results compared to those from hygrothermal simulation. Differences are identified between the two methods in the quantification of the moisture buffering potential, which lead to further investigation on the effect of ventilation and moisture transport through the entire wall assembly. The significance of this paper is to show building moisture regulation involves also different factors, such as ventilation and walls moisture transport, which will impact the moisture buffering potentials indoors. Consequently, it is necessary to better understand moisture buffering in real buildings, to quantify the influence of hygroscopic materials indoors, and introduce alternative laboratory testing, to give quantitative information about their impact in buildings.

*Keywords:* materials, dynamic sorption capacity, hygrothermal performance, ventilation, moisture transfer

## 1. Introduction

Indoor environment humidity levels have an important influence on occupant health and well-being. Relative Humidity (RH) in buildings influences thermal comfort and the perception of indoor air quality [1], and when it is too low or too high, the risk of developing allergies and other diseases is increased [2]. To lower these risks and keep RH to optimal (between 40% and 60%), energy consuming air conditioning system are often used.

It is possible to improve indoor air quality, as well as reducing the overall energy consumption of mechanical devices through passive control of room humidity. Through exposure of hygroscopic, vapour active, materials to the room air indoor humidity fluctuations can be moderated. The use of vapour

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responsive materials such as clay plaster reduces the peaks of internal relative humidity due to their good moisture buffering capacity [3, 4, 5].

Testing methods, such as the NORDTEST protocol [6], ISO 24353 [7],JIS A 1470-1 [8] and DIN 18947 [9] have been developed, to quantify dynamic sorption capacity. These protocols are based on the step-response method, which consists in monitoring the mass change of samples, subjected to cyclic RH square wave fluctuations [10]. Tests are undertaken in controlled environments, in which temperature is constant and humidity varies cyclically. Material mass variations are continuously recorded to quantify the amount of water adsorbed and desorbed during the humidity cycles. Even though the principle of these protocols is the same, each method presents different boundary conditions, which makes a comparison between the methods not possible. Together with the time and RH steps, the surface film resistance is a factor that depends on the air velocity and geometry of the materials. Consequently, a variation of both air speed [11], material properties and dimensions [12] produce variations in the moisture buffering performances. Table 1 shows the main differences between the three testing methods.

Table 1: Summary of moisture buffering protocols

| Protocols | RH Steps | Time-Steps | Surface Film Resistance ($m^2\dot{s}Pa/kg$) |
|---|---|---|---|
| NORDTEST (2005) | 75%-33% | 8h-16h | $5.0 \times 10^7$ |
| ISO 24353 (2008) | 55%-33%<br>75%-53%<br>95%-75% | 12h-12h | $4.8.0 \times 10^{13}$ |
| JIS A 1470-1 (2002) | 55%-33%<br>75%-53%<br>93%-75% | 24h-24h | $2.4 - 9.4 \times 10^7$ |

The step-response tests do not also represent the moisture buffering behaviour of finishing materials (materials applied on indoor surfaces, like plasters or wooden panels) in real buildings, as the participation of other factors, including wall-build up, ventilation,the presence of surface coatings and furnishing to the indoor moisture balance is not considered [13]. Consequently, it is important to observe the complementary effects of these phenomena on moisture buffering, as they can increase or reduce the dynamic sorption capacity of hygroscopic materials.

Latif et al. [14] showed that wall assemblies can reduce moisture buffering performances of plasters, if less hygroscopic sub-layers are used. The study demonstrated the moisture buffering capacity of hemp-lime insulated walls was always reduced, if other materials were applied on top of it. Nonetheless, the application of only lime plaster kept the assembly's moisture buffering capacity high, compared to the other cases, where lime was applied on top of gypsum plasterboard or air barrier.

Yoshino et al. [15] highlighted the direct impact of ventilation on moisture buffering. Higher the air speed and ventilation rate, lowered the sorption capacity of finishing materials, until it reaches a maximum ventilation rate, which makes moisture buffering impact in houses negligible [16]. Ventilation also adds or removes moisture in buildings, depending on the outdoor weather conditions. In wet or rainy locations, ventilation moves the moist air indoors, while in dry environments, the moisture produced indoor migrates outdoors. It is evident the outdoor weather influences the indoor environment specifically the humidity, as demonstrated by Nguyen et al. [17] through statistical linear correlation between indoor and outdoor environmental conditions from experimental data. Consequently, the geographical location of the buildings is always to be considered, when analysing moisture buffering.

Buildings infiltration has been also observed to dry finishing materials near the leakages [18], which means infiltration helps the vapour desorption phase. However, it is not easy to quantify this behaviour, as outdoor vapour concentration is not constant, and it can be higher than the indoor, causing vapour to move from the outdoors to the indoors. The results obtained in this study were obtained in a heated space and in a cold environment, which highlights their dependency to the boundary conditions, and can be associated with condensation.

Ramos et al. [19] demonstrated that the application of paints reduced the moisture buffering capacity of materials. Consequently, it is necessary to look at the vapour permeability of coatings, to allow plasters or other hygroscopic materials to buffer the indoor humidity. Several researchers [20, 21, 22] also highlighted the importance to consider the effect of furnishing indoors. Yang et al. [20] demonstrated that placing furniture in front of walls reduced the wall moisture buffering potential, as the active surface area is considerably reduced. However, the furniture itself is capable of buffering humidity, which needs consequently to be considered in the moisture balance equation together with walls [23]

It is necessary to analyse material behaviour in real contexts, to better understand moisture buffering influence in buildings. However, experimentation on real buildings is not often possible, leading toward the use of simulation. As a result, laboratory testing can be modelled on simulated buildings behaviour, and give a real quantification of the dynamic sorption behaviour of materials.

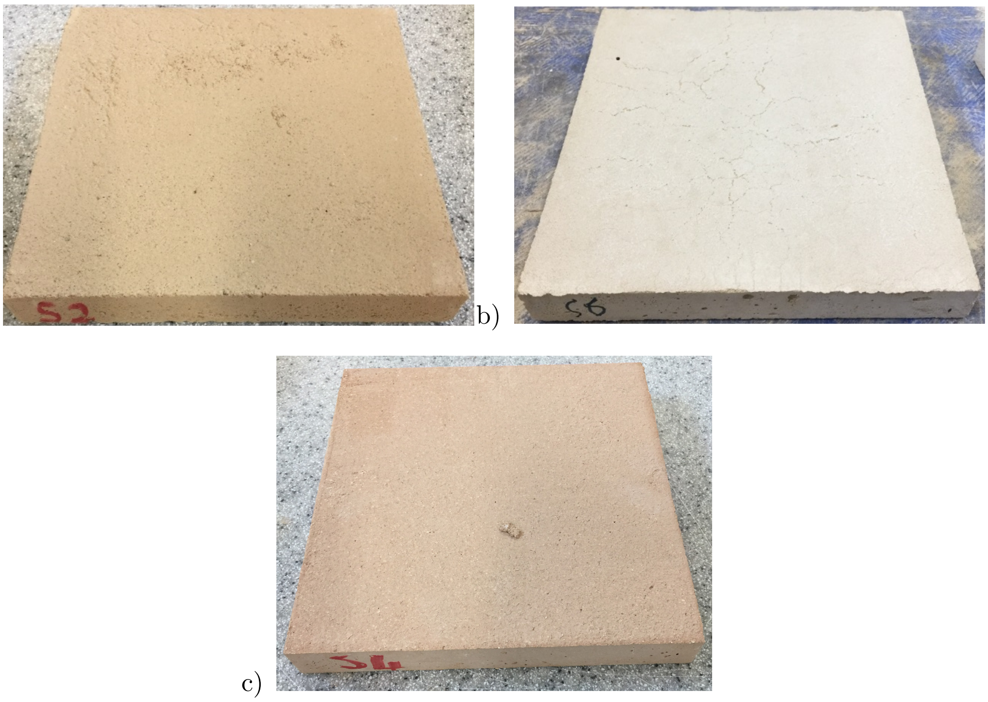
The objective of this study is to establish the degree of discrepancy in the moisture buffering potential of three coatings (clay, gypsum and lime plasters) in experimental testing and full-scale building simulations. Simulation were set up, to cyclically expose the room to 8 hours of humidification, followed by 16 h de-humidification, in order to follow the step-response humidity function of the laboratory step-response protocol. The differences between the two measurements led to further simulation analysis. The effect of ventilation and moisture transport into the enclosure were analysed, to explain the reason of the significant gap between testing and simulations. The aim was to better understand the impact of moisture buffering on buildings and the influence of ventilation and the overall "breathability" of the wall assembly on the dynamic sorption capacity, to push towards the development of alternative testing method, which can give realistic information on the hygrothermal performances of building materials indoors.

## 2. Materials

Commercially available clay, lime and gypsum plasters were mixed and tested. The kaolinitic clay plaster was composed of 69% sand, 25% silt and 5% clay [24], while gypsum was a lightweight calcium sulphate hemihydrate. Lime was natural moderately hydraulic lime (NHL 3.5) with a compressive strength of 3.5 $N/mm^2$.

### *2.1. Specimen preparation*

The clay, gypsum and lime plasters were mixed by a mechanical mixer in the laboratory. To the air dry clay plaster and gypsum were added a further 20% and 30% mass of water respectively . The lime plasters was mixed with fine aggregate sand (sieved to remove particles bigger than 1 mm and mixed in a ratio of 1.2:5 of lime:sand) and 30% mass of water. The water ratio was set according to the workability of the materials. Specimens were cast in 150 x 150 x 20 mm moulds made with phenolic-faced plywood. Thereafter, the specimens were stored for 28 days before testing in an environmental chamber at 20°$C$ and 60% RH.



a) b) c)

Figure 1: Moisture buffering specimen: a) clay, b) lime, c) gypsum plasters

## 3. Laboratory Methods: Requirements for Simulations

Three specimens for each materials were used for testing the density, water vapour permeability and moisture buffering. For the thermal conductivity, one specimen for each materials was cut with a rotating blade to obtain smaller samples with seven measurements for each material. The sorption capacity was measured from small plasters pieces, made by breaking the originally cast specimens.

### *3.1. Density Vapour Diffusion Resistance Factor*

The bulk density was measured after drying the materials in the oven at $105°C$, until weight stabilised. As a requirement of the 3D hygrothermal simulation software WUFI® (Wärme- Und Feuchtetransport Instationär), the 'Dry' cup method [25] was applied to determinate the vapour diffusion resistance factors of the samples. After the specimens were pre-conditioned in climatic chamber at $23°C$ and 50% RH for 24 hours, they were sealed with aluminium tape on the top of a plastic container, to ensure vapour tight-seal. For the dry cup test Calcium Chloride ($CaCl_2$) was used to obtain 0% humidity inside the plastic container. As the ISO 12572 (2016) [25] requires, an air layer of 1.5 cm thickness was kept between salt and internal sample surface. The assembly was then placed in a climatic chamber (ACS DY110) at $23°C$ and 50% RH and weighed every 24 h (Ohasus Pioneer$\pm 0.01\, g$ readability) until constant rate of change of mass had been achieved.

### *3.2. Thermal Conductivity*

Thermal conductivity was measured on 75 x 75 mm samples at ambient temperature ($19°C$ 63%RH), after 72 hours in the air conditioned room, where the test was performed. Tests was performed with a KD2 Pro at the Indian Institute of Science, Bangalore. The KD2 Pro (precision ±10%) is a transient method instrument, which is equipped with a dual needle inserted inside the specimen. The heat is applied to one of the two needles for a set time and the other one measures the temperature variations. For this study the holes for the needles were drilled before conditioning. During the test no filling liquid was applied between the needles and the specimen, as the adhesion seemed acceptable. The thermal conductivity at ambient conditions was measured 7 times at an interval of 15 minutes between measurements, in order to dissipate the thermal gradients.

### *3.3. Vapour Adsorption/ Desorption Curve*

The sorption isotherm was measured by a Dynamic Vapour Sorption (DVS Intrinsic Water Sorption Analyser) apparatus at the constant temperature of $23°C$. The humidity range was from 0% to 90% with experimental accuracy of mass change ±0.1 mg. The temperature and RH precision of equipment are respectively $\pm 0.2°C$ and ±1%. Three specimens with a mass of approximately 0.3 mg were placed on the DVS scale and the surrounding humidity was increased gradually in steps, until mass variations were less than 0.02 g. The change in mass (%) of the plasters samples was measured.

### *3.4. Moisture Buffering*

Three specimens for each plaster were tested, following the NORDTEST protocol [6]. The samples were placed in an environmental chamber on a mass balance to continuously record the mass variation (one sample every minute). The climatic chamber was programmed to pre-condition the samples at 50% and $23°C$ for 24h, and to perform 6 cycles of 24h each at 75% RH for 8h and 33% for 16h. Specimens were covered by a screen to reduce the air speed to less than 0.1 m/s. The Moisture Buffering Value (MBV) is expressed in $g/(m^2 \cdot \%RH)$.

## 4. Hygrothermal simulation

### *4.1. Simulation theoretical model*

For thermo-hygrometric simulation of the building, WUFI®Plus V3.0.3 was chosen, as it was demonstrated it is the most accurate commercially available software for moisture buffering analysis [26]. In this model the transport of heat and humidity in the building structures is described with the following equations [27]:

$$\frac{dH}{dT} \cdot \frac{dT}{dt} = \triangledown \cdot (\lambda \cdot \triangledown T) + h_v \cdot \triangledown(\delta_p \cdot \triangledown(\phi p_{sat})) \tag{4.1}$$

$$\frac{dw}{d\phi} \cdot \frac{d\phi}{dt} = \triangledown \cdot (D_\phi \cdot \triangledown \phi) + \delta_p \cdot (\delta_p \cdot \triangledown(\phi p_{sat})) \tag{4.2}$$

where: $\phi$ is the relative humidity (-), t is time, T is the temperature ($°C$), w is the moisture content ($kg/m^3$), $p_{sat}$ is the saturation vapour pressure (Pa), $\lambda$ is the thermal conductivity (W/mK), H is the total enthalpy ($J/m^3$), $D_\phi$ is the liquid conduction coefficient ($kg/m \cdot s$), $\delta_p$ is the vapour permeability ($kg/m \cdot sPa$), $h_v$ is the latent heat of phase change (J/kg).

The indoor absolute moisture ratio ($c_i$ $[kg/m^3]$) is calculated from the following water vapour mass balance equation:

$$V\frac{dc_i}{dt} = \sum_f A \cdot \dot{g}_{wj} + nV(c_a - c_i) + \dot{w}_{Imp} + \dot{w}_{Vent} + \dot{w}_{HVAC} \tag{4.3}$$

where: $c_a$ and $c_i$ are respectively the absolute moisture ratio of the exterior and interior air, $\dot{g}_{wj}$ is the moisture flux from the interior surface into the room, $\dot{w}_{Imp}$ is the moisture production, $\dot{w}_{Vent}$ and $\dot{w}_{HVAC}$ are respectively the moisture gains or losses due to ventilation and HVAC systems

### *4.2. Study Case*

A single test room, located at the University of Bath's Building Research Park, Wroughton, UK was modelled. The cell's external dimension is 4.34 x 4.34 x 2.94 m, while the internal dimension is defined by the uniform wall thickness (404 mm). As shown in Fig. 2, the walls are composed of lightweight cavity, comprising of, from outside to inside, exterior concrete block, air gap, PIR insulation and aerated concrete blocks. Floor and ceiling are timber sandwich panel structure of PIR insulation and particle board with a total thickness of 350 mm. Walls have a measured U-value of $0.26\,W/m^2K$, which was measured on site by heat flux sensors and thermocouples applied on the north wall. Floor and ceiling have a calculated U-value of $0.10\,W/m^2K$, determined following the EN ISO 6946 (2007) [28]. The internal aerated concrete block surface was coated alternatively with 20 mm thickness clay, lime and gypsum plaster, whilst the floor, ceiling and door were covered with an impermeable layer ($sd = 1500\,m$), in order to ensure that the room moisture balance is not affected by the particle board. Simulations of this test structure was chosen in preference to field testing to avoid the cost and complexity of re-plastering and installation of mechanical ventilation.

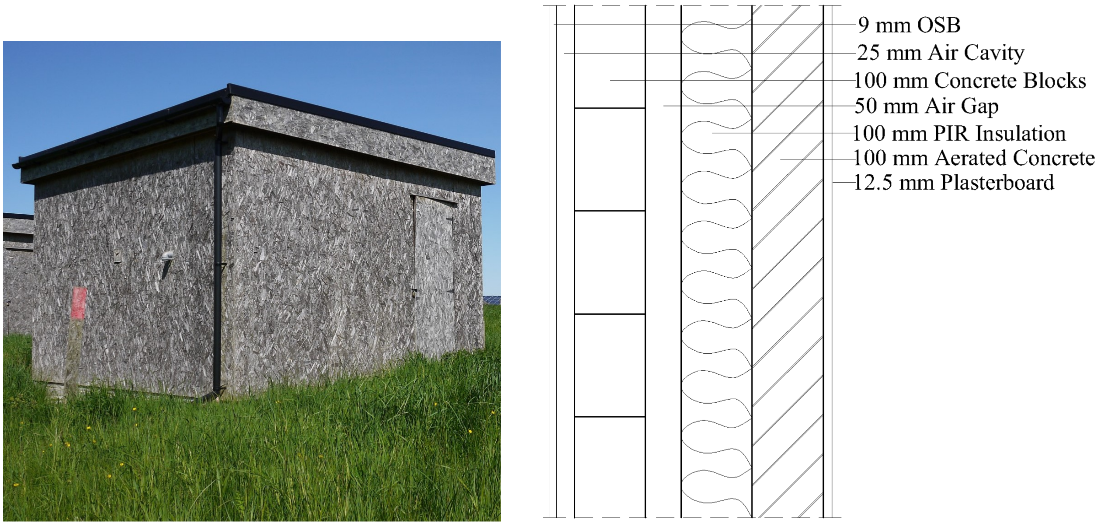



Figure 2: Test buildings and wall section.

The indoor temperature and humidity behaviour of the test room was simulated over a 4 year time-frame. It was necessary to run pre-conditioning for one year to start the actual simulation period with more realistic values. The first year simulation was run without any moisture generation source, to let the room reach the equilibrium with the surrounding environment. This operation was necessary, as the software considers user-defined initial temperature, RH and water content in each wall layer, which in most cases do not represent the real condition of 5 year old building. From the second year the room was subjected to a daily constant water vapour generation, which simulated an occupancy of two people during the night between 11.00 p.m. to 7.00 a.m. The amount of water vapour correspond circa to $120\,g/h$ at a constant temperature of $23°C$ [29]. The natural ventilation rate was then set to a constant $0.5/h$. The reason of such a small ventilation rates was to minimise the risk of condensation in the room, without reducing the moisture buffering potential of the walls. The infiltration rate applied to the model was measured on-site through a gas decay test in the test cell, which measured a value equating to 0.017 $h^{-1}$. No furniture was used in simulations. The indoor temperature was kept constant at $23°C$, while the outdoor climatic data were taken from the BRP weather station (Gill Instruments MetPak II plus RM Young tipping bucket rain gauge, and Delta T SPN1 Sunshine Pyranometer Devices), placed around 20 m from the test room. Fig. 3 shows the monitored weather data for 2018. The south west of England weather presents high temperature and RH diurnal and seasonal variations. Winters are cold and dry, while summers are mild, except for short heat waves. However, rain is frequent, which often leads to a high RH of the air in the local outdoor environment. The reference weather year is the 2018 (Fig. 3), which showed consistent high humidity levels, with minimum RH below 50% recorded only during one of the heat wave in June.

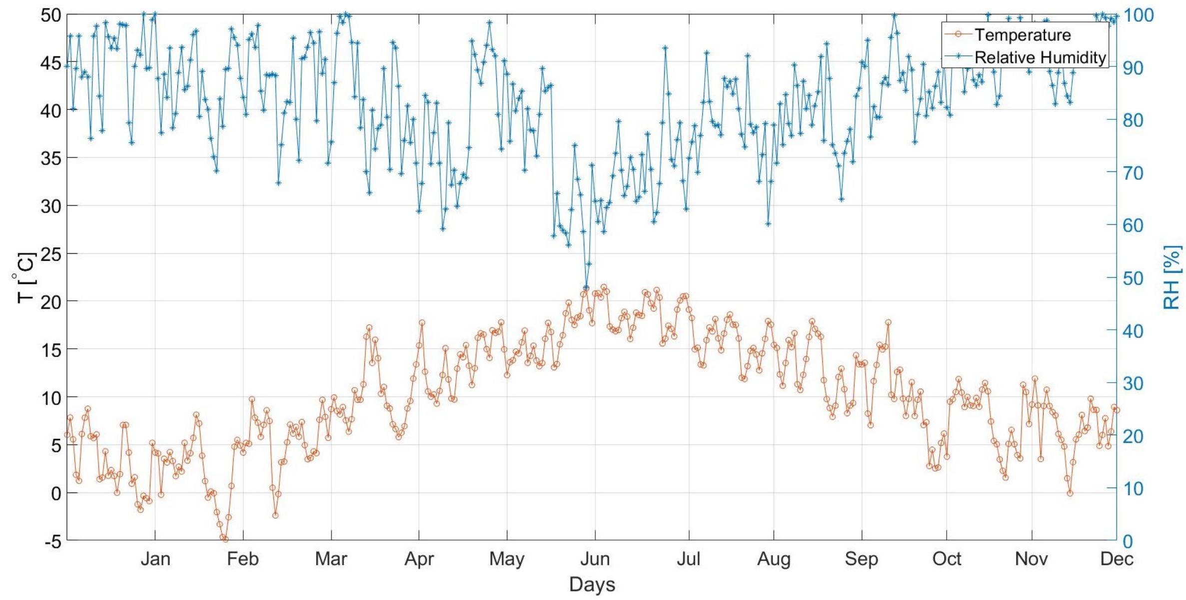


Figure 3: Outdoor Temperature and RH data used for simulations.

The computational analyses were performed for four simulated wall internal finishes, clay plaster, lime plaster, gypsum and a vapour barrier ($s_d = 1500$). Plaster hygric properties are reported in Table 3, while porosity ($\epsilon$) and thermal properties (Table 2) were obtained from a review of published literature: for clay, [30] and [31], for lime, [32] and [33] and for gypsum, [34] and [35].

Table 2: Material properties of plaster materials

| Material | $\epsilon(\%)$ | $c\,(J/kgK)$ |
|---|---|---|
| Clay | 27.4 | 849 |
| Lime | 33 | 929 |
| Gypsum | 65 | 1150 |

## 5. Results

### 5.1. Material properties

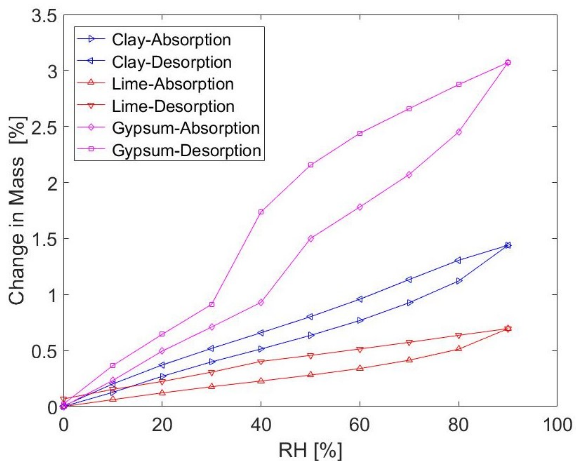
Table 3 presents the measurement results of density ($\rho_{dry}$), water vapour resistance factor ($\mu$), thermal conductivity ($\lambda$) and coefficient of variation (CoV).

Table 3: Measured hygrothermal properties of three plasters

| Material | $\rho_{dry}(kg/m^3)$ | CoV (%) | $\mu(-)$ | CoV (%) | $\lambda(W/mK)$ | CoV (%) |
|---|---|---|---|---|---|---|
| Clay | 1258 | 2.32 | 24.45 | 0.82 | 0.44 | 1.23 |
| Lime | 1590 | 1.69 | 19.62 | 6.15 | 0.38 | 0.63 |
| Gypsum | 890 | 0.95 | 8.37 | 4.27 | 0.18 | 0.89 |

The sorption isotherm for clay, lime and gypsum is shown in Fig. 4a. Two cycles were performed to ensure the stability of the sorption curves, with only the second curve used for analysis. The increase in water content from 0% RH to 90% RH for clay and lime can be approximated as linear, while gypsum shows a different sorption curve and greater gap between adsorption and desorption. The different behaviour of gypsum results in a Type IV curve [36, 37], due to the possible bigger pore diameter and higher capillary condensation. Lime also presents an anomaly, as there is a mass increase of 0.08% at the end of the full cycle of absorption and desorption, indicating the lime binder may not have completed its hydration. Clay presents higher sorption capacity than in Maskell et al. [24], probably due to the higher amount of water used for casting, but the clay used for this research adsorbed less vapour than in [38], because of its lower content of clay. Overall, gypsum reached higher values of moisture content, approximately 3.1% mass at 90% RH, compared to the clay (1.5%) and lime (0.7%). Moisture buffering test results also highlighted that lime did not reach a balance after 6 cycles. Tests were repeated and an increase of around 3% weight every cycle was again observed in lime, always due to the hydration process. Nonetheless, clay and gypsum have similar buffering performance (Fig. 4b): after 8 hours of humidification they reached respectively a Moisture Buffering Value (MBV) of $1.67\,and\,1.60\,g/(m^2 \cdot \%RH)$, whereas lime reaches only $0.95\,g/(m^2 \cdot \%RH)$.

The laboratory test showed clay and gypsum plaster exchange more humidity than lime, while other studies showed similar moisture buffering values for clay [3, 5, 39], but gypsum presented in general moisture buffering values lower than $0.95\,g/(m^2 \cdot \%RH)$. However, the moisture buffering results for gypsum presented by Stahl et al. [5] and Santos et. al. [40] show a plateau, which indicates the material reached its maximum capacity. Consequently, gypsum cannot be compared with these studies. Lime plaster performances are in line with Tittarelli et al. [41] and Stahl et al. [5] results, in which lime mixed with sand has the worst MBV performances (0.50-0.88 $g/(m^2 \cdot \%RH)$).



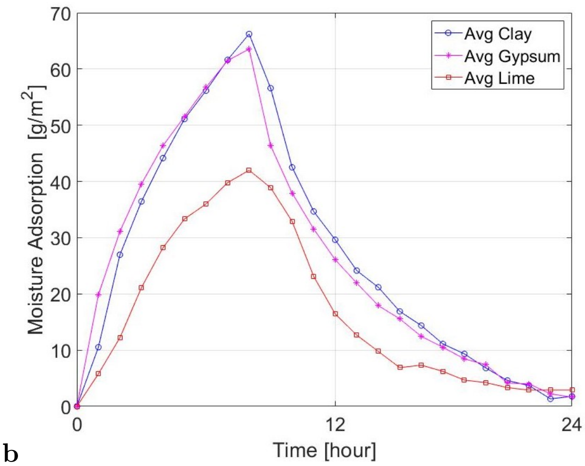




Figure 4: Sorption isotherm curve and moisture buffering profile of clay, lime and gypsum.

### *5.2. Full Scale Moisture Buffering Simulation*

Simulation of all internal walls was carried out. The discrepancies of the results between walls was negligible, as less than 2%. For this reason, in this paper only the results from the East wall are shown, as representative of all walls' behaviour. As Fig. 5 shows, the test room responded quite effectively to humidity moderation and reduced the peaks, when plasters were applied on internal surfaces. Plasters reduced the moisture fluctuation by at least 23% RH, compared to the impermeable walls case (when no hygoscopic materials are applied on the surface). Eight days at the end of June are randomly presented in Fig. 5, to show the daily moisture changes. However, the whole analysis was performed on the average yearly data.

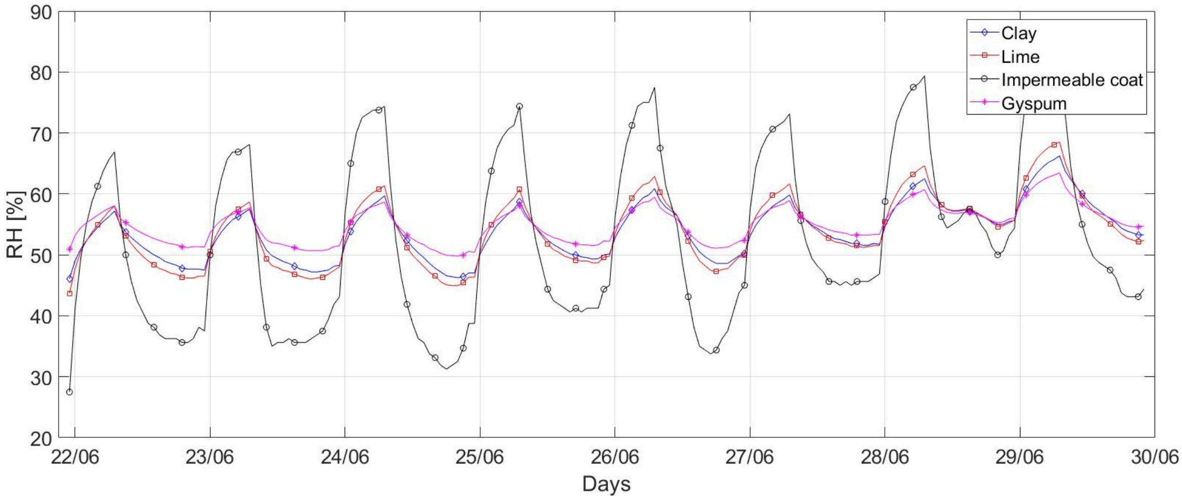



Figure 5: RH variation in the simulated room.

Gypsum plaster demonstrated the higher moisture buffering capacity, while lime plaster performed least effectively. Fig. 5 indicates that for clay the average indoor relative humidity peak-to-peak amplitude was reduced to 10.8% RH in the indoor environment, compared to the non-hygroscopic room (37%), whilst lime had a lower impact in the room (13.0% RH). Gypsum adsorbed a greater proportion of the generated moisture, as humidity fluctuation are reduced to 6.3%. The water vapour sorption in the materials was also analysed and it showed the difference between the materials was modest. Gypsum, clay and lime adsorbed and desorbed, $10.4\,g/m^2$, $9.6\,g/m^2$ and $8.7\,g/m^2$ respectively. It indicates an increase of $1\,g/m^2$ in the dynamic sorption capacity produces a bigger impact on the humidity in the room.

## 6. Analysis and Discussion

### *6.1. Effect of Ventilation on Moisture Buffering*

Experimental results and simulations indicated the improved moisture buffering of gypsum material compared to lime and clay plaster, even though the sorption capacity between the three materials was only of $1\,g/m^2$. It is evident the differences between the two tests was not only in the different materials performances, but there was also a significant gap in the quantification of the moisture buffering capacity. Step-response test gave higher materials' moisture buffering performances compared to simulation, as shown in Fig. 6.

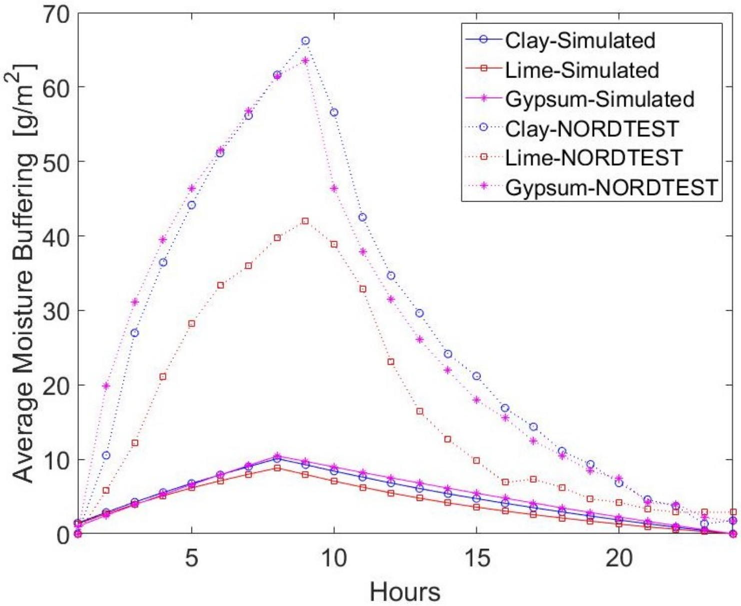



Figure 6: Moisture Buffering comparison: step-response test and simulation results.

The simulation output presented both lower average moisture buffering values and smaller differences between the three plasters. The results of experimental methods presented a much greater average moisture buffering value and a much higher performance of clay and gypsum plaster, compared with lime plaster. These differences may be due to the use of steady-state material properties in the software, which do not represent the real moisture buffering behaviour of the wall [42]. However, [26] showed that simulation and experimental results agree, when the test set up is replicated in the simulations. It means the participation of other phenomena to the moisture balance in the room, e.g. ventilation, infiltration and humidity transport mechanisms in the test room enclosure, as well as the subsurface wall build up (as demonstrated by [14]), are responsible of the gap between full-scale and laboratory tests.

Infiltration and ventilation influenced the plasters' ability to modify the humidity concentration in the room, as they participated to the moisture uptake in buildings. Ventilation also influenced the surface resistance, increasing or decreasing the moisture buffering potential, depending on the air velocity generated. Fig. 7 illustrates how ventilation removed moisture from the environment, together with plasters, in order to balance the moisture content in the room. Ventilation moisture removal reached the peak in correspondence of the humidification period, probably due to the significant water vapour pressure difference between the indoor and outdoor. In the dehumidifying phase ventilation kept removing moisture at a lower rate, while walls compensated the moisture losses in the room, releasing humidity. The only exception can be seen in Fig. 7 on the $28^{th}$ of June, in which the ventilation transported moisture into the room, as in that particular day the outdoor vapour pressure was higher than the indoor one.

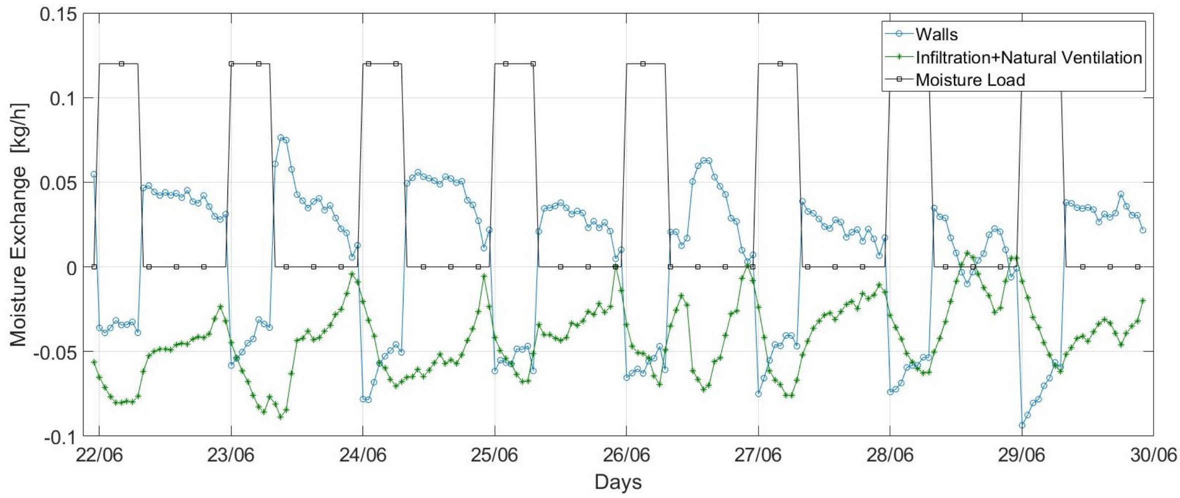


Figure 7: Influence of ventilation and walls in the moisture exchange with clay plaster

Table 4 summarises the simulated moisture buffering of walls and ventilation, when the three different plasters were applied on the walls. Gypsum presents again a better moisture buffering capacity relative to the other two materials, as it was able to gain more vapour from the environment, and at the same time it reduced of 8.22% the amount of moisture expelled through ventilation, compared to the other two cases. In general, Table 4 clearly shows walls played a more important role in the moisture regulation of the indoor, as they buffer between 66.87% to 81.20% of the humidity excess in the building, when the air change per hour was low. Table 4 represents the annual moisture buffering average, but through the year, there were some days were the contribution of ventilation jumped to 0.11 kg/h, and the impact of the walls dropped to 0.07 kg/h. It means moisture buffering impact in buildings was relative to ventilation, due to the higher pressure differential between the indoor and outdoor. The moisture balance is the difference between the quantity of water released by the humidifier and the water buffered between walls and ventilation. It shows walls and ventilation removed most of the moisture from the room, while a small amount of moist air was controlled by other factors, like the ceiling, floor and door. Even though an impermeable sheet was applied on these elements, the software calculated a small amount of water vapour managed to pass through the water vapour barrier.

Table 4: Yearly average of the moisture exchange between the indoor space, walls and ventilation.

| Material | Load (kg/h) | Walls (kg/h) | Ventilation (kg/h) | Moisture Balance (kg/h) | Walls Impact (%) | Vent. Impact (%) |
|---|---|---|---|---|---|---|
| Clay | 0.12 | 0.10 | 0.04 | -0.02 | 72.97 | 27.03 |
| Lime | 0.12 | 0.09 | 0.05 | -0.02 | 66.87 | 33.13 |
| Gypsum | 0.12 | 0.11 | 0.02 | -0.01 | 81.20 | 18.80 |

### *6.2. Moisture Transport in Walls and Moisture Buffering Capacity of Sub-Layers*

To investigate the extent that materials underneath the plasters participated to the moisture buffering, it was necessary to inspect theses layers without interference from other variables. Simulations without the humidity source in the room were run, to first quantify and eliminate the impact of outdoor weather to the overall moisture transport in walls. Simulations with and without moisture source were then compared and the effect of weather was subtracted from the simulated humidification results. In contrast with moisture penetration reported in [24], simulations showed that the Autoclaved Aerated Concrete blocks (AAC), underneath the plaster, actively participated in the moisture buffering process. Fig. 8 shows the daily moisture content fluctuations in the AAC. Gypsum and lime presents 0.51 and 0.88 $g/m^2$ fluctuations respectively (5% and 10% of the total moisture buffering capacity), which were less marked in the case with clay plaster (0.22 $g/m^2$ and 2.5% of the total sorption capacity), probably due to the lower water vapour permeability of clay.

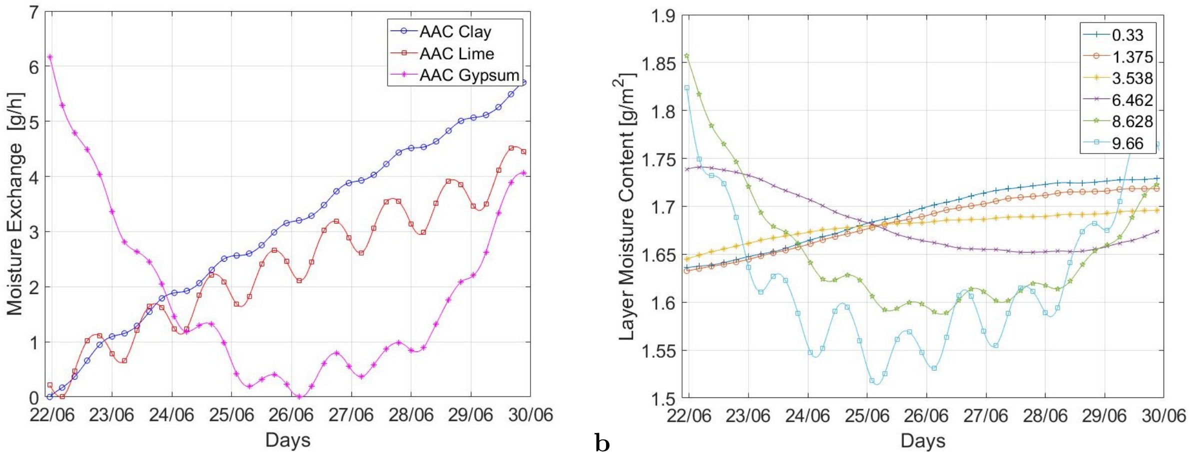


Figure 8: Left: contribution of the aerated concrete block to moisture buffering; Right: water content distribution in the AAC for gypsum.

The AAC in the gypsum plaster case presents a different behaviour across the 8-days (Fig. 8a), and also across the year (Fig. 9). When clay and lime were applied, AAC tended to have a steady linear behaviour; its water content increased during spring until August, and desorbed water in the following Autumn (Fig. 9). In the gypsum simulation, AAC still maintained the seasonal moisture buffering behaviour (Fig. 9), but it was also effected by shorter humidity variation cycles, as showed in Fig. 8a.

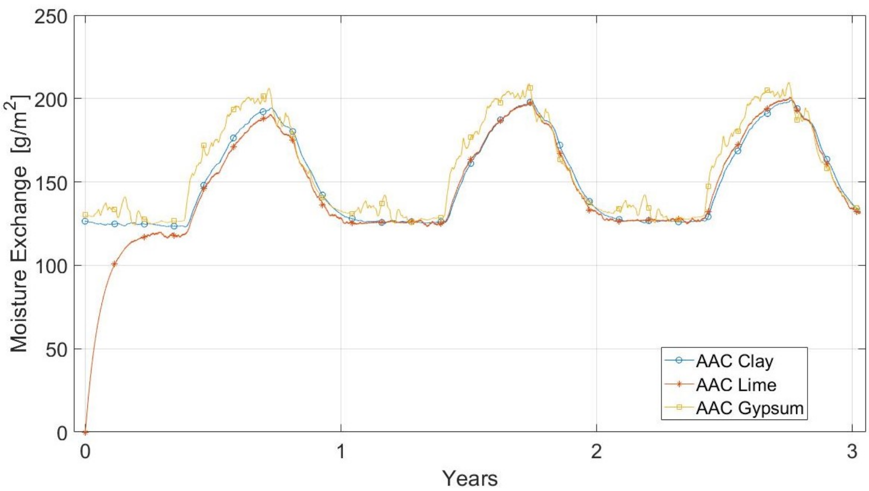


Figure 9: Yearly trend of AAC in the three simulated cases.

Inspecting the moisture content of the plasters in the selected 8 days (Fig. 10a and c), lime and clay show a constant and steady moisture buffering behaviour. It indicates there was a stable daily moisture adsorption and desorption cycles. These plasters also allowed moisture to move into the AAC, which keeps storing water over the summer season and released it in autumn, helping a seasonal balance (Fig. 9). On the contrary, gypsum never reached a balance with the environment (Fig. 10b), and for this reason, it keeps adsorbing water, until around the $6^{th}$ day.

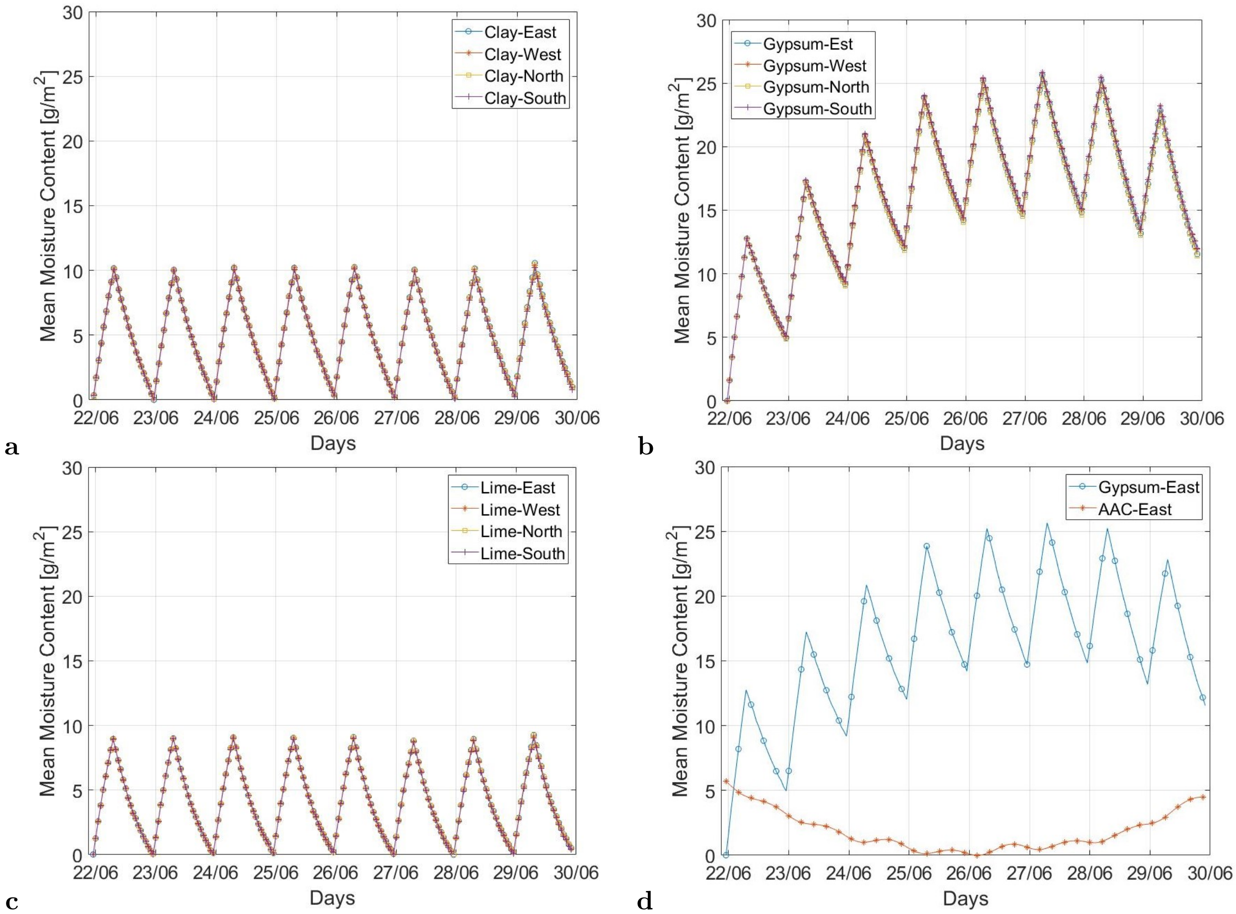



Figure 10: Plasters moisture buffering equilibrium: from top left clockwise clay, gypsum, gypsum and AAC, lime

This implies that gypsum is not only subjected to daily fluctuations, but does help to buffer humidity in weekly, monthly or seasonal RH variations. Consequently, AAC has an opposite trends to gypsum, as AAC balances the moisture in the room together with the plasters, as illustrated in Fig. 10d. When gypsum reaches the moisture peak, less water moves into the AAC and vice verse.

To confirm this complementary work between the plaster and the AAC, the moisture distribution in the AAC was analysed. The water content was analysed, from the outdoor to the indoor, at 0.33, 1.37, 3.54, 6.46, 8.86 and 9.96 cm. Results show the inner layer (the one closer to the plaster) is more influenced by the humidity fluctuation in the indoor, the outer layer (0.33) is more affected by outdoor weather condition (Fig. 8b).

It can be stated breathable sub-layers may actively participate to the indoor moisture buffer, when coatings have high water vapour permeability, like for gypsum. Their complementary support in the buildings' moisture balance helps regulating not only the daily RH fluctuation, but also weekly and seasonal variation, due to the activation of moisture transport mechanism.

## 7. Conclusions

Moisture buffering capacity of clay, lime and gypsum coatings was determined experimentally and through hygrothermal simulations. The NORDTEST procedure was performed on small samples in a climatic chamber, while the behaviour of plasters in a building was simulated in WUFI®.

The laboratory test showed clay and gypsum coatings exchange more humidity than lime, while simulation presents much smaller moisture buffering values than experimentally determined. For gypsum the laboratory testing returns very different results to those obtained from the simulation. The NORDTEST presents a regular and steady moisture buffering capacity of gypsum, while simulation shows a more unpredictable behaviour, due to its higher sensitivity to humidity changes. The comparison between simulation and the step-response test highlighted the moisture potential of materials differed, as experimental testing does not consider the effect of ventilation and the participation of the other wall components to the indoor humidity mitigation.

It was shown that ventilation, combined with building air infiltration, participated to the moisture buffer of the room, even though plaster had a higher impact on the indoor moisture buffering regulation. This demonstrated the positive impact porous materials have on the humidity regulation, when buildings are air tight or low ventilation strategies are applied (like in cold environment). However, it is possible that higher air change per hour may reduce the moisture buffering involvement of materials.

The computational model also revealed the deeper penetration of water vapour into the wall from the room, passing though the plasters. This mechanism may be partially attributed to the water vapour permeability of the finishing materials and the vapour pressure and temperature differential between the indoor and outdoor environment, as well as to water transport mechanism between different materials. However, this behaviour needs to be verified, as simulations were based on the static material properties, which means the results are based on the average adsorption curve of gypsum and its water vapour permeability. Further analysis will assure the causes of the water transport, and verify if hygrothermal simulations magnify this process, as based on simplified models and laboratory tested materials properties.

The significance of this study is to improve moisture buffering understanding, showing that in buildings the ventilation and moisture transport though the wall also participate the moisture regulation. The precise evaluation of the impact of moisture buffering in buildings will lead to the development of an experimental test, which can precisely quantify the amount of buffered moisture. This would bring to an optimisation or introduction of new finishing materials. An increased understanding of the impact of natural plasters on the hygrothermal comfort will also push to a major use of breathable materials to improve the indoor environment, and to reduce the usage of "active" conditioning system energy consumption.

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